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13. ABSTRACT (Maximum 200 words)
The purpose of this project was to design, construct and test a ground source heat engine that would operate on the temperture difference between the air and the ground to produce a small amount of electrical power. During the design phase, expressions for an optimally matched heat exchanger and thermoelectric module configuration were derived. A prototype was constructed according to the design procedure developed in the first phase of the project using an off-the-shelf thermoelectric module. The prototype was instrumented and tested over an extended period. It was found that the relationship between the temperature drop across the thermoelectric module and the total air-ground temperature difference varied with the time of day. Part of this variation was attributed to direct solar insolation in the afternoon. A rough estimate of the potential generation with optimally matched custom components indicated an increase in output by a factor of nineteen. Most of the electricity generation (78%) occurred between the hours of noon and 4pm during the period of this test (April-May at 33°N latitude).

14. SUBJECT TERMS
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Final Progress Report

Design and Construction of a Ground-source Heat Engine

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Statement of the Problem Studied

The objective of this project was to design, build, and test a prototype thermoelectric generator capable of producing small amounts of electric power using the temperature difference between the ground and the atmosphere as the energy source.

At most locations outside the tropics, the diurnal temperature changes in the air near ground level are large compared with the temperature changes even a very short distance below the surface of the ground. In concept, these daily temperature differences can be harnessed by a heat engine to produce power. In practice, the temperature differences are of the order of 10^0 to 10^1 K, in surroundings close to 300 K, so that the thermal efficiency of any such heat engine will be small. This means that a large amount of heat must be moved through the device for each unit of power produced. As with many natural power sources, there is an enormous amount of energy, but very little availability.

The system consists of a thermoelectric module sandwiched between a heat exchanger in contact with the atmosphere and a heat exchanger buried in the ground. When the air temperature is higher than the ground temperature, heat flows into the system primarily via convection from the air, radiation from the sun, and radiation from the surroundings. Heat is rejected to the cooler ground by conduction. The thermoelectric module connects the hot side and cool side and generates electricity from the temperature difference. At times when the ground temperature is higher than the air temperature, the system still produces power but all heat flows are reversed. The central issue of the design problem was in bringing the relatively large heat flows into and out of the thermoelectric module with a minimal temperature drop so that the thermoelectric module operates at its highest efficiency.

This system has several advantages over other power generation systems. First, by using a thermoelectric generation module, there are no moving parts in the entire system. This will result in a long design life with little maintenance. With no moving parts the system can be designed to be extremely rugged and insensitive to handling and transport. Since half the system is underground and the other half is only exposed to the atmosphere, the system has a relatively low visibility profile. The system generates power both when the air temperature is higher than the ground temperature and when it is lower than the ground temperature. Direct sunlight is beneficial, but is not be necessary for the system to function. Unlike fragile photovoltaic panels, the thermoelectric couple is sturdy by itself, and is further protected by being completely enclosed by the structural and heat transfer surfaces around it. The enclosure also provides protection from corrosion and other environmental effects.

Summary of the Most Important Results

*First phase: (development of design procedures and design of a prototype)

- –derivation of the optimum burial depth for a ground-source device to exchange heat with the ground
- –development of a simple approximate method for designing a system which has the thermoelectric module optimally matched with the heat exchangers if the reservoir temperatures are fixed
- –development of the optimal system design for cases of time-varying thermal resistance in the heat exchangers
- –presentation of the overall design sequence for ground-source thermoelectric heat

engines

–completion of a parametric numerical study of the ground-side heat exchanger performance

–generation of a rudimentary predictive model of the ground-side heat exchanger performance suitable for system design

–design of a prototype including selection of commercially available thermoelectric modules, and designs for air-side and ground-side heat exchangers

*Second phase: (construction and testing of the prototype)

–completion of the construction of a ground-source heat engine prototype

–assembly and testing of a portable data acquisition system for measuring the performance of the prototype

–preliminary testing

–long duration testing

–data reduction and analysis

–determination of the relationship between the total air-ground temperature difference and the temperature drop across the thermoelectric module as a function of the time-of-day

–estimation of the performance penalty incurred by using off-the-shelf components that were not optimally matched

–establishment of the long term average electricity generation profile

–establishment of the long term electricity generation distribution by time-of-day

Publications

(a) Papers published in peer-reviewed journals

•J.W. Stevens, "Optimal Design of Small ΔT Thermoelectric Generation Systems," *Energy Conversion and Management*, Vol. 42, pp. 709-720, 2001.

(b) Papers published in conference proceedings

•J.W. Stevens and A. Fox, "Quasi-steady Heat Conduction From a Buried Finned Cylinder," *Proceedings of the 35th National Heat Transfer Conference*, Anaheim, CA, paper NHTC2001-20047, June 10-12, 2001.

•J.W. Stevens, "Heat Transfer and Thermoelectric Design Considerations for a Ground-source Thermoelectric Generator," *The International Conference on Thermoelectrics, 1999*, Baltimore, MD, paper MO-WHEO.1, Aug 29-Sep 2, 1999.

•J.W. Stevens, "Optimized Thermal Design of Small ΔT Thermoelectric Generators," *The 34th Intersociety Energy Conversion Engineering Conference*, Vancouver, B.C., paper 1999-01-2564 , Aug 2-5, 1999.

(c) Papers presented at meetings, but not published in conference proceedings

•J.W. Stevens, "Underground Heat Transfer: Heat Engines and Reservoirs," Portland State University, Faculty and Students, April 16, 2001

- J.W. Stevens, "Underground Heat Transfer: Heat Engines and Reservoirs," University of Colorado at Colorado Springs, Faculty and Students, April 12, 2001

- J.W. Stevens, "Underground Heat Transfer: Heat Engines and Reservoirs," University of Colorado at Denver, Faculty and Students, May 9, 2000

- J.W. Stevens, "Energy Harvesting: A Ground-source Thermoelectric Generator," DARPA Energy Harvesting Program Review, Arlington, VA, April 14, 2000

- J.W. Stevens, "Energy Harvesting: A Ground-source Thermoelectric Generator," Mississippi State University, Faculty and Students, September 9, 1999

- J.W. Stevens, "Underground Heat Transfer: Heat Engines and Reservoirs," Brigham Young University, Faculty, April 12, 1999

- J.W. Stevens, "Design and Construction of a Ground-source Heat Engine," Mississippi State University, Faculty and External Advisory Committee, October 9, 1998

(d) Manuscripts submitted, but not published

- J.W. Stevens, "Performance Tests of a Prototype Ground-source Heat Engine," *6th IASTED International Conference: Power Generation and Renewable Energy Sources (PGRES 2002)*, Marina Del Rey, CA, USA, May 13-15, 2002, in review.

(e) Technical reports submitted to ARO

–no technical reports

Participating Scientific Personnel

–Andrew Fox; student working on M.S. in mechanical engineering

Report of Inventions

–no inventions